General Response:

The authors would like to thank the reviewer for all the helpful comments and suggestions which will help make the manuscript better. The reviewer had 5 major concerns, 1) There was too much data presented in the manuscript without clear organization, 2) That the motivation for using RegCM3 was not clearly outlined, 3) The methods for how the permanent El Niño was generated was unclear, 4) The superrotation section needs clarification, and 5) the Soil moisture feedback analysis needs to be defined better. We agree with these comments and have improved the manuscript by more fully motivating and describing these aspects.

I. Major Comments:

Major Comment 1. There is so much data presented in the figures that it is unnecessarily hard to pick out the features alluded to in the text. I count a total of 85 different spatial fields being presented in the work, which seems excessive. I think this partly a consequence of a slight lack of focus in the piece – be more assertive about which conclusions you want to convey and it should become clear which figures need inclusion.

The authors agree that there were many figures and a lot of discussion in the text. The hope was to explain the relevant dynamics which are induced by a permanent El Niño and much of what was included was necessary to tell the entire story. In the revised manuscript, Figure 10 and Figure 12 will be removed and discussed within the context of Figure 11. These figures were removed because Figure 11 shows the relevant dynamics needed for the results and discussion of summertime precipitation changes induced by our permanent El Niño.

Figure 11 (Now figure 10) will also be reduced into 2 panels showing the boreal summer anomalies rather than a month by month decomposition. Additionally, Figure 13 (Now figure 12) will also be reduced to a three panel plot showing just the correlation between soil moisture and precipitation for the NINO simulation only as suggested by the reviewer.

Finally, the regional circulation results (3.4.2) and soil moisture section (3.4.3) has been reworded to be more concise and will only include key points. The specific text changes and improvements are mentioned throughout the minor points section of this response.

Major Comment 2. I was not certain what was gained by the inclusion of the RegCM3 results. I assume that the global model does not satisfactorily describe the paleo-observations of the hydrological cycle over North America. However, this was never actually shown. It felt like you were trying to solve a problem that I was not sure actually existed.

1. We have added text to the Methods section (subsection 2.2) clarifying that (1) Our primary motivation for high-resolution nesting is to better resolve fine-scale processes that can be important for the response of regional climate to changes in global-scale forcing or changes in large-scale climate dynamics; (2) Much of this work has been focused on the response of regional climate in North America to elevated greenhouse forcing and late-Quaternary orbital forcing, and suggests that fine-scale processes can regulate the response of a number of important regional climate features, including seasonal temperature, extreme temperature and precipitation events, snow-melt runoff, and atmosphere/soil-moisture coupling; and (3) Given the

previous work suggesting the importance of fine-scale processes in shaping the regional-scale climate response to changes in greenhouse and orbital forcing, we nest the RegCM3 high-resolution model within the CAM3.0 global model in order to test the role of fine-scale climate processes in shaping the regional hydroclimatic response to permanent El Niño-like SSTs.

2. We have added text to the Methods section (subsection 2.2) further describing the RegCM3 simulation of present climate features over North America. This includes text stating that because of its higher resolution representation of the atmosphere and land surface, RegCM3 is able to better resolve fine-scale atmospheric features and climate system feedbacks than the lower resolution GCM, and of particular relevance for this study is the fact that RegCM3 is better able resolve the regional precipitation features in the U.S. than CAM3.0.

3. We have added a comparison of the regional and global model data with paleoproxy data as a new Figure 1. This data proxy comparison includes Pliocene and Miocene records and shows how the global and regional results compare with the current proxy record. We have added text to the Methods section (subsection 2.2) stating that (1) the differences in the simulation of baseline precipitation between the low- and high-resolution models are particularly evident over areas for which proxy records of Pliocene and Miocene precipitation exist, including the topographically complex Western US in winter and coastal areas of the eastern U.S. in summer, and (2) given the geographic correspondence of the model differences with the locations of proxy observations, and the documented importance of fine-scale climate processes for the regional climate response in North America to changes in global radiative forcing and large-scale climate dynamics, we are motivated to use a high-resolution climate modeling system to test the role of fine-scale climate processes in regulating the regional hydroclimate response to permanent El Nino-like SST conditions.

Added to methods section 3.2

The differences in the simulation of baseline precipitation between the low- and high-resolution models are particularly evident over areas for which proxy records of Pliocene and Miocene precipitation exist, including the topographically complex western U.S. in winter and coastal areas of the eastern U.S. in summer (Fig. 1 and 3-in revised manuscript). Given the geographic correspondence of the model differences with the locations of proxy observations, and the documented importance of fine-scale climate processes for the regional climate response in North America to changes in global radiative forcing and large-scale climate dynamics, we are motivated to use a high resolution climate modeling system to test the role of fine-scale climate processes in regulating the regional hydroclimate response to permanent El Nino-like SST conditions.

4. We have added text to the Results section (subsection 3.5) describing how the model precipitation results compare with the geologic proxy record. Specifically, we have added text stating that (1) the simulated response of precipitation to permanent El Niño-like SSTs captures the wetter-than present conditions inferred from the proxy data; (2) the regional model simulates more wide-spread moistening in the Western and Central US than the global model, and the drier conditions over the Pacific Northwest indicated by Thompson, 1991 and Retallack, 2004 are resolved in the regional model, but not in the global model; (3) comparison of the high-resolution regional model and the lower-resolution global model suggests that topographic complexity

influences the regional response of precipitation to the El Nino SST forcing, but that the spatial contrasts in magnitude of moistening are not testable with the proxy reconstruction shown here.
Added results section 3.5

A compilation of available proxy records for the Miocene and Pliocene were gathered and compared with the permanent El Niño induced precipitation anomalies at the global and regional scale (Fig. 1). This analysis is an extension to the proxy comparison completed in Molnar and Cane, 2007. In this compilation, we have enhanced the amount of proxy records for the eastern U.S. and added additional sources in the western U.S. At the global scale the proxy records match the permanent El Niño driven precipitation values very well over North America, South America, Northeast Africa (Bonnefille, 2010), Mediterranean regions (Jimenez-Moreno et al., 2010), Canada (White et al., 1997), and Indonesia (Amijaya and Littke, 2005). The model precipitation does not match the record as well over Central Africa (deMenocal, 1995), parts of Asia (Sun et al., 2010) and Japan (Heusser and Morley, 1996) (Fig. 1a). When comparing with the blueprint seen in Molnar and Cane, 2002, the model data comparison matches with the exception of Central Africa where our model results are drier than the proxy record (deMenocal, 1995). Wetter conditions are seen in North America, Europe, northwestern and southeastern South America, and drier conditions are seen in northeastern South America (Fig. 1a). In addition, Australia has contradictory reconstructions for precipitation, but our results do match the areas of drying seen in (Metzger and Retallack, 2010) and mentioned in Molnar and Cane, 2002.

In order to develop a more detailed knowledge of the past pattern of hydrological change and perform a higher resolution model-data comparison. A regional scale precipitation and proxy comparison was completed over the U.S. using RegCM3 (Fig. 1b). While preparing the comparison significant effort was devoted to locating inferred precipitation records over the Eastern U.S. To date, previous studies focused on temperature differences (Cronin and Dowsett, 1991) between the Neogene warm periods and modern (Molnar and Cane, 2002, 2007; Bonham et al., 2009). Using proxies and vegetation cover described in Braun, 1950, Martin and Harrell, 1957, and Litwin and Andrle, 1992, results show expansive deciduous and temperate forests in the eastern U.S. It was inferred that this climate and vegetation cover could only be sustained by increased modern rainfall in the Miocene and early Pliocene (Fig. 1b). Increased precipitation along the eastern U.S. is also suggested by Willard et al., 1993, but this study also indicates little change of precipitation in Florida. The modeled permanent El Niño precipitation over the eastern U.S. is able to capture this wetter pattern seen in the proxy records.

The western U.S. has received substantial attention by climate scientists and geologists because of its susceptibility to large-scale droughts (Cook et al., 2004; Cole et al., 2002). Most proxy records in the western US for the Neogene warm periods indicate wetter than modern with the exception of Thompson, 1991 and Retallack, 2004, which suggest drier conditions in Pacific Northwest in the late Pliocene. The simulated response of precipitation to permanent El Niño-like SSTs captures the wetter-than present conditions inferred from the proxy data. The regional model simulates more wide-spread moistening in the western and central U.S. than the global model, and the drier conditions over the Pacific Northwest indicated by Thompson, 1991 and Retallack, 2004 are resolved in the regional model, but

not in the global model (Fig. 1). In addition, comparison of the high-resolution regional model and the lower-resolution global model suggests that topographic complexity influences not only the baseline precipitation of the western U.S., but also the regional response of precipitation to the El Nino SST forcing, with reduced moistening on the lee side of the Pacific-coast high elevations. However, the spatial contrasts in magnitude of moistening are not testable with the proxy reconstruction shown here.

II. Some other more minor points are:

i. The description of the method is missing an essential sentence or two

Revised description of methods:

We create a permanent El Niño-like SST boundary condition by low-pass filtering the historical observed SST field and adding this anomaly to the 12 month climatology derived from Hurrell and Trenberth, (1999). Observed SSTs taken from ERA-40 data set were linearly detrended and then low pass filtered to remove variability shorter than three years. A cross-correlation analysis with SST variations in the Niño 3.4 region was carried out and the resulting correlation field was the basis for the imposed SST anomalies. The cross-correlation field was scaled by the local standard deviation of SST (i.e. regressed) and by an arbitrary and globally constant coefficient designed to scale the imposed SST anomaly in the Eastern Equatorial Pacific to be comparable to the values reconstructed by Dekens et al. 2008. A threshold of 1/10 of this constant coefficient was imposed to mask out very small SST anomalies which are not likely to represent the core forcing of the Permanent El Niño response. We then add the low-pass-filtered SST anomalies to the NCAR climatological SST from Hurrell and Trenberth(1999). The permanent El Niño absolute SST distribution and anomaly can be seen in Fig. 2. This is a highly idealized permanent El Niño and the anomaly is constant in all months in the repeating 12 month SST specified field.

ii. The citations did not always address the points made in the sentence
This is fixed within the text. There are many short comments below which address these points all of which are fixed in the revised manuscript.

iii. Some of the discussion may benefit from inclusion in the results section, as it summarizes the findings and explains the importance of them
This point is a good one and added discussion was included into some portions of the results section. Improvements will be mentioned throughout the rest of the short comments below.

iv. I got a little lost in the section on superrotation. I was not expecting your model to show it, as none of Barreiro et al. (2006), Vizcaino et al. (2010) or Brierley Fedorov (2010) report such a feature. The text seemed to start off with this expectation, and then say that it was pretty common after all. I still do not understand why your simulation is shows superrotation, whilst these other do not (not that you necessarily need to address this here)
Superrotation can be expected when a sufficiently strong, zonally localized heating anomaly is present on the equator. This is the case in our NINO simulation, as the imposed SST anomaly

does in fact produce a shift of the warm pool maximum to the central Pacific (See Figure 1a-in revised manuscript). In Barreriro et al and Vizcaino et al, the SSTs have no zonal gradient in the equatorial Pacific and thus do not produce a zonally-confined heating anomaly, so their simulations do not show superrotation. We have reorganized the text on page 12 to clarify this point.

v. The soil-moisture feedback analysis seemed to address a different question to elsewhere in the piece (about processes impacting variability within the NINO simulation, rather than differences between NINO MOD).

The point of the soil moisture section was too explore the connection between increases in soil moisture to changes in relative humidity and precipitation in the NINO simulation. The correlations between soil moisture and relative humidity/precipitation in the MODERN case were not statistically significant and thus were not included in the Figure. Thus we presented the absolute NINO correlation fields that highlight what is enhanced due to a permanent El Niño. Specific clarifications and revised text are discussed below in the reviewers specific comments section.

<u>III. The following are more detailed comments about the different sections of the article</u>

<u>Introduction</u>
I found the use of references in the introduction a little lop-sided. There are several instances of many references being cited, but without really verifying the point made in a sentence with multiple stated facts. The very first sentence provides an example of this issue. It states that the Miocene and Pliocene were 2-3˚C warmer globally despite small changes in CO_2 levels, yet of the 6 citations 3 deal with CO_2 variations, 2 with the climate of North America and one with the Pacific. None of these describe a global mean temperature change of 2-3˚C, which, as a quantitative estimate, must come from somewhere.

More citations were added for this sentence in the introduction to address the global temperature estimations for the Pliocene and Miocene. In addition, the wetter and drier regions outlined in the introduction all had references added to them along with the model and proxy comparison section.

Added text for Pliocene and Miocene warmth (introduction-page 1):

Within the Neogene (~23-2.58 mya), the early and middle Miocene tropical SST regions were warmer than modern by 1-2˚C (Stewart et. al., 2004; You et al., 2009) and close to modern values in the late Miocene (Steppuhn et al., 2007), but spatial coverage is lacking especially in the eastern equatorial Pacific (EEP). While terrestrial temperatures in the mid-latitudes are recorded as warmer than modern in the early and middle Miocene (Wolfe, 1994; Uhl et al., 2006; Micheels et al., 2007). In the early Pliocene, the tropical SSTs are recorded as up to 8˚C(Dekens et al., 2007; Brierley et al., 2009; Brierley and Fedorov, 2010) warmer than modern, with continued warmth in the middle to late Pliocene

(Dowsett, 1996). Global temperatures during the middle Pliocene are reconstructed as 2–3˚C warmer globally compared with modern (Raymo et al., 1996) with warmer than modern mid-latitude regions (Thompson and Fleming, 1996).

Kurschner reference is actually 2008 (p201-page3, l6)
Fixed

No references for wetter-than-modern conditions in pre-Quaternary (p201-page3, l20). So haven't really shown the "regional aridity paradox" exists.

References were added to this sentence to illustrate the wetter mid-latitude regions especially over North America. Also included is the new data proxy comparison Figure 1.

Added text for Pliocene and Miocene wetter in mid-latitudes (introduction-page 1):

These warmer periods are also reconstructed as having wetter mid-latitude regions over North America (Thompson, 1991; Thompson and Fleming, 1996; Smith and Patterson, 1993; Smith, 1994; Wolfe, 1994, 1995; Cronin and Dowsett, 1991) Europe (Jimenez-Moreno et al., 2010; Boyd, 2009), and South America (Zarate and Fasana, 1989).

This response to elevated greenhouse forcing appears at odds with widespread evidence for wetter-than-modern and cooler conditions over North America (Smith, 1994; Thompson, 1991; Axelrod, 1997; Wolfe, 1995; Cronin and Dowsett, 1991) and wetter conditions over Europe and Central South America in the Neogene warm periods.

Alter commas in "jet, data, theory and models" (p202-page-4 l 1) as it reads awkwardly.
Fixed

No discussion of either Molnar Cane (2007) or Bonham et al. (2009) on p202-page4, l15.

A discussion was added for these references:

Revised text in introduction page- 6:

Bohnam et. al., 2009, explored Pliocene mid-latitude teleconnections that developed due to altering the boundary conditions and found that changing vegetation could match some of the Pliocene proxy record. To further explore the hypothesis suggested by Molnar and Cane (2002), Huybers and Molnar (2007) used modern empirical estimates of high latitude temperature driven by El Niño events to understand the teleconnected response the Equatorial Pacific SSTs may have had on the gradual cooling in the high latitudes over the late Pliocene. Molnar and Cane, 2007, used large modern El Niño events and associated teleconnections to compare with the Miocene and Pliocene proxy record.

Description of Barriero et al (2006) method is incorrect. They extended dateline SSTs.
Barriero et. al., 2006 methodology was corrected in text (example in Introduction Page-6)

Barreiro et al. (2006) removed the east-west SST gradient in the Pacific, and extended the dateline SSTs to better understand the high-and mid-latitude temperature changes resulting from the El Niño teleconnections.

You describe the methods of previous studies permanent El Nino studies in the introduction, but do not summarize any of their findings.

Since previous permanent El Niño simulations had different fundamental questions than our study we decided to only describe how our methodology was different from previous simulations.

There is considerable repetition between the first 2 paragraphs on P203-page 5.
Sentences were tightened and repetition was removed.

<u>Method</u>

The sentence referring to Joseph Nigam is confusing (p204--page 6, l8). I'm unsure whether realistic teleconnections in a coupled model with an "incorrect" ENSO signal really show that the atmospheric model is correct. The following sentence could also benefit from rewording.

This sentence is reworded in revised manuscript. The point of this sentence is to show that CAM3.0 is able to capture observational El Niño teleconnections even when coupled to an ocean model. This is surprising because the coupled model is unable to capture the temporal variability of El Niño events.

Revised text in methods section 2.1 page 7:
CAM3.0 when coupled to the ocean model captures the observed atmosphere response to ENSO forcing during the wintertime even though the fully coupled model has problems reproducing the temporal variability of El Niño events.

The description of creation of the SST field is highly deficient. Low-pass filtering alone will still give an interannually-varying SST field, with features of both El Niño and La Niña. You need at least one other sentence explaining how you go from this to an El Niño anomaly. I'm a little unsure whether you add a single anomaly throughout the year, or a monthly varying one that does not change from year to year (both could fit with p204, l22). Henceforth, I'll assume that it is a constant one. You haven't stated the source or time-period of your observed dataset.

Text added to the methods section 2.1:

We create a permanent El Niño-like SST boundary condition by low-pass filtering the historical observed SST field and adding this anomaly to the 12 month climatology derived from Hurrell and Trenberth, (1999). Observed SSTs taken from ERA-40 data set were linearly detrended and then low pass filtered to remove variability shorter than three years. A cross-correlation analysis with SST variations in the Niño 3.4 region was carried out and

the resulting correlation field was the basis for the imposed SST anomalies. The cross-correlation field was scaled by the local standard deviation of SST (i.e. regressed) and by an arbitrary and globally constant coefficient designed to scale the imposed SST anomaly in the Eastern Equatorial Pacific to be comparable to the values reconstructed by Dekens et al. 2008. A threshold of 1/10 of this constant coefficient was imposed to mask out very small SST anomalies which are not likely to represent the core forcing of the Permanent El Niño response. We then add the low-pass-filtered SST anomalies to the NCAR climatological SST from Hurrell and Trenberth (1999). The permanent El Niño absolute SST distribution and anomaly can be seen in Fig. 2. This is a highly idealized permanent El Niño and the anomaly is constant in all months in the repeating 12 month SST specified field.

I believe the anomaly is a global field, as it doesn't state otherwise. Please be explicit about this, because obviously the teleconnections will be differently represented. However, the two references for the Pliocene are solely on the Equator – comparison with a more global reconstruction would be relevant (e.g. PRISM or Brierley et al, 2009). "as the" on p205, l8 p206, first paragraph. I think this point would be better shown with the inclusion of some observations to act as a truth (probably replacing the difference plot). As you state this is only an illustration, a single period may be sufficient.

Text added to the methods section 2.1:

The resulting SST patterns are broadly consistent with proxy based SST reconstructed for the equatorial Pacific in the Pliocene (Wara et al., 2005; Dekens et al., 2008) and are comparable in magnitude to those in Vizcaino et al. (2010). The low pass filtered SST anomaly was chosen to focus on SST configurations that are potentially long lived, i.e. not strongly damped on 1-2 year time scales by ocean-atmosphere interaction. Because the anomaly was derived from the Niño 3.4 region it projects both the "Modoki-type" (Fig. 2a) as described in Ashok et al., 2007 and "canonical" ENSO variability. The resulting SST field has peak SSTs along the dateline comparable with the 20th century SST trends (Collins et al., 2010; Sang-Wook et al., 2009).

<u>Results</u>

You state the observations give an SST change of 2-3oC (p206, l16---page 8), yet figure 1a shows values in excess of 5oC, which is twice as large rather than "in close agreement".

This SST anomaly comparison is a spatial average of the entire El Niño which comes to around 2-3˚C because there are temperature anomalies in the Eastern Equatorial Pacific ranging from 0.5C to greater than 5C. To avoid confusion this sentence will be removed in the revised manuscript.

Revised text in section 3.1 (page 10)

The permanent El Niño conditions increase simulated global mean temperature by 0.27˚C. This global temperature anomaly is similar to the approximately 0.2˚C anomaly seen in the strong El Niño of 1997/1998 (Hansen et al., 2006). By design, the permanent El Niño SST pattern is consistent with a typical large El Niño event, as seen in the simulated NINO minus MODERN surface temperature anomaly (Fig. 2b).

Please alter colorbar in Fig1a, so that each level has an individual color, rather than 3-5oC sharing orange.
The color bar was adjusted in the revised manuscript

Please be careful when stating numbers: 0.272oC seems to imply excessive accuracy, 0.27oC would do.
Fixed

There is no need to refer to Fig1b three times in consecutive sentences (p207, ll15-22).
Adjusted in text

Superrotation
I found this section a little awkward to understand. Firstly, I had some issues with the text discussing the winds in NINO state, whilst the figure only shows anomalies from a reference state that is not shown.

The NINO state has westerly winds at the equatorial tropopause of about 20 m/s; a line has been added (page 11) to make this clear.

The discussion seems to imply that superrotation should be expected from the inclusion of any SST anomaly, yet I was left uncertain as to why this should be the case. I know that simulations with minimal SST gradients (e.g. those of Barriero et al. , 2006) do not show superrotation. I think in part this confusion goes back to my uncertainty of NINO SST field, and whether your SSTs lead to an SST maximum in the central Pacific larger than that of the west Pacific warmpool, or simply a relaxation/removal of the zonal SST gradient along the Equator. One could naively think that the zonal wind anomalies in fig 3f might cancel on the zonal mean (note there is no scale for this panel). Yet again I wonder if showing the actual circulations rather than just anomalies might be helpful here.

Superrotation can be expected when a sufficiently strong, zonally localized heating anomaly is present on the equator. This is the case in our NINO simulation, as the imposed SST anomaly does in fact produce a shift of the warm pool maximum to the central Pacific. In Barreriro et al and Vizcaino et al, the SSTs have no zonal gradient in the equatorial Pacific and thus do not produce a zonally-confined heating anomaly, so their simulations do not show superrotation. We have reorganized the text on page 12 to clarify this point.

"One could naively think that the zonal wind anomalies in fig 3f might cancel on the zonal mean (note there is no scale for this panel). Yet again I wonder if showing the actual circulations rather than just anomalies might be helpful here."

The winds shown in 3a and 3f are eddy winds, ie. the zonal mean has been removed; so the zonal average of the winds shown in the figures will indeed average to zero. The caption to Fig. 3 has been amended to clarify this point, and a length scale is now included in 3f. Since the paper already contains a large number of figures, we prefer not to introduce new figures showing the mean fields.

Regional Results

I was surprised there was no mention of Canada in the discussion, considering the largest DJF anomalies exist there. Perhaps it is too close to the edge of the domain, but even that should be mentioned. Another reason for mentioning Canada is the impact of a permanent El Nino on ice sheet formation has been a focus of previous research (e.g. Huybers Molnar, 2007 and Brierley Fedorov, 2010)

Discussion of Canada was added in this section with appropriate discussion of previous work. We also mention how the shifts in stormtracks and increases in meridional heat transport are important in increasing surface temperatures in Canada during El Niño events.

Revised text in results section 3.3-page 14

Surface air temperature decreases are isolated to the Southeast and Southwest in December-January-February (DJF), with temperatures increasing over the Pacific Northwest (Fig. 5c) and into Canada which can be seen clearer in the global temperature plots. This response is induced by increased meridional heat transport from the tropics into the poles (Figure not shown). The warming over Canada and Alaska during El Niño events is important for changes in sea ice in the Northern Hemisphere and has been the focus of previous permanent El Niño research (Huybers and Molnar, 2007; Brierley and Fedorov, 2010).

This section reads rather like a description of the figures, some additional interpretation (that would not be immediately gleaned from looking at the figures) would improve the style of the section.

This is a good point, text was reworded in order to clarify the main points of our results.

In Fig 4, the conventional abbreviation of Sept, Oct Nov is SON.
Fixed

In Fig 5, the color bar has many more contours that color. Has a significance test been applied to the features on this figure, as there are large regions of white?
Yes a significance test was applied and a threshold was applied to create the color bar. This has been mentioned in the revised figure caption.

With both figure 4 and 5, I was uncertain what was gained by including five separate panels – do the paleobservations have this level of temporal resolution?

The majority of previous studies have focused on DJF when describing El Niño teleconnections. We wanted to show precipitation and temperature results for all seasons to show the entire seasonality for this type of permanent El Niño. Even though some proxies do not have this temporal resolution maybe in the future this can be used in climate and proxy comparisons.

Additionally, our dynamical analysis spans all seasons so the authors felt it was important to show the precipitation and temperature anomalies in all seasons. This is especially important for the soil moisture values because the enhanced rainfall in the winter further enhances the precipitation and soil moisture values in the spring and summer.

Revised text in results section 3.4.2 (page 16)

The progression of springtime and summertime precipitation patterns are decomposed into their MAM and JJA precipitation anomalies to explore the seasonality of permanent El Niño induced precipitation anomalies because the winter precipitation is linked to increases in precipitation and soil moisture values in the spring and summer.

Example for this motivation added in results section 3.4.2 (page 18)

As described above in the seasonality of precipitation, the longer memory introduced into the regional climate system by the winter precipitation anomalies causes spring and summer to be moister. These results motivate why we show the seasonality of precipitation and soil moisture.

<u>**Stormtracks**</u>

P211, l5--page 13. This sentence states (VQ), yet the figures use V'Q'. Please incorporate the equation here, rather than in the figure caption and be consistent in your labelling

The correct labels were added into the text and equation was described in text.

The stormtrack analysis appears correct, but I was left wondering how this tied into the temperature and precipitation feature you had just described (especially Canadian winter warming). Perhaps you could move your discussion to here, before heading onto other features.

This is a good point and we have added some basic discussion in the results section (3.3 and 3.4.1). For our purposes the focus of the stormtrack analysis was to explain why there are precipitation anomalies over the east and west coast of the United States. The diagnostics are trying to isolate the movement in stormtrack direction and intensity. A full analysis of Canadian warming is beyond the scope of our analysis and is more related to heat transport from the tropical regions. To make this clearer we have replaced Figure 7 and 8 with new figures that show spatial fields and anomalies for integrated mean moisture flux convergence and integrated transient moisture flux convergence which illustrates how water vapor is being transported in the Atlantic and Pacific Ocean. In results section 3.4.1 we explicitly describe what is inducing the large shift in boreal winter precipitation.

Example in Results Section 3.4.1:

To quantify the changes in moisture transport we decompose the moisture flux into the mean component and transient eddy response over North America, utilizing standard meteorological definitions of the reynolds decomposition for scalar and vector fields. We

then calculate the vertically integrated moisture flux convergence by the time mean and transient eddy component. (Fig. 8). The integrated moisture flux for the time mean circulation is calculated by integrating the convergence of the time mean quantities for over the entire atmospheric column. The transient eddy integrated moisture flux is calculated by subtracting the time averaged fields from instantaneous fields and then doing the integration of the transient eddy convergence over the entire atmospheric column (Higgins et al., 1997; Castro et al., 2001).

Results show that the integrated moisture flux by the mean flow increases over the western U.S., but not over the east coast of the United States in the NINO case (Fig. 8a) relative to MODERN (Fig. 8b). When taking the anomaly between the NINO and MODERN case this results in an anomalous increase in the integrated moisture flux convergence over the western U.S. and an increase in moisture flux by the mean wind directed toward the western United States (Fig. 8c).

The transient eddy integrated moisture flux in the NINO case exhibits a southward shift in the integrated moisture flux over the east and west coasts of the United States. The NINO case has increases in the integrated moisture flux in the east coast of the United States and the transient eddy moisture flux is directed from the central Atlantic toward the east coast of the United States (Fig. 2e). The transient eddy integrated moisture flux does not increase over the west coast of the United States indicating that the increases in precipitation over the western U.S. are not induced by the transient eddies.

In summary, the precipitation over the west and east coast of the U.S. are controlled by different mechanisms. The mean integrated moisture flux is responsible for the increases in precipitation over the western U.S. (Fig. 8c) as the mean zonal wind shifts southward altering the amount of moisture entering the western United States. In the east coast, the transient eddies direct moisture onshore increasing the integrated moisture flux (Fig. 8f) and precipitation (Fig. 6c).

Regional scale circulation changes

It required effort to grasp the point you were trying to make with this section. A little bit of rewording and adding a summary at the end of the section would help with this. I think it would also benefit from only figures necessary to the story being shown - perhaps just fig 10.

Soil feedbacks

This is a good point, there were some results that should not have been mentioned in this section. This section was reworded and re-written to only include regional circulation and precipitation patterns over the United States. An introduction and quick summary were added to the beginning and end of this section to illustrate key points (section 3.4.2).

Added text in section 3.4.2

Motivated by previous work suggesting the importance of fine-scale processes in shaping the regional-scale climate response to changes in global radiative forcing, we have used the RegCM3 high-resolution model to test the role of fine-scale climate processes in shaping the regional hydroclimatic response to permanent El Niño-like SSTs. Here we analyze the RegCM3 results to explore the regional precipitation and circulation anomalies that

develop in the boreal spring and boreal summer due to a permanent El Niño. Analysis will aim to explain the seasonality of precipitation anomalies, the lower level circulation, and moisture availability over the U.S.

Added text in section 3.4.2

In summary, winter-like dynamics persists in the Pacific sector until late spring causing a southward drift in stormtracks which induces precipitation increases over the east and west coast of the United States. During boreal summer, increases in moisture availability in the lower atmosphere and a shift in lower level mean wind allows convective precipitation to entrain deep into the continental US. These mechanisms are integral in increasing precipitation in the U.S. in boreal spring and summer.

I was a little uncertain as to what this subsection was attempting to prove. Are you saying the NINO-MODERN anomalies are enhanced by soil moisture feedbacks? As you concentrate on anomalies within an individual simulation, I am unsure whether you have tackled this issue. Instead, I think you are testing whether soil-moisture feedbacks were stronger within the permanent El Niño climate.

The point of the soil moisture section was too explore the connection between increases in soil moisture with changes in relative humidity and precipitation in the NINO simulation. The correlations between soil moisture and relative humidity/precipitation in the MODERN case were not statistically significant and thus were not included in the figure. Thus we presented the absolute NINO correlation fields that are significant highlighting what is enhanced in the NINO simulation. Specific clarifications and revised text are discussed below in the reviewers specific comments section.

Added text in results section 3.4.3 (Page 18)

In our experiments, the NINO case has increased surface soil moisture in Pacific Northwest and Midwestern U.S. starting in April and stays elevated throughout JJA. To explore the connection between soil moisture and precipitation we lag correlated soil moisture and different atmospheric variables by averaging May through August and lagging precipitation and relative humidity against the May through August average of soil moisture contents (Fig. 12). Correlation are done with the NINO test case only because all correlations we calculated with the MODERN simulation were not statistically significant.

I would expect land surface changes to enhance the NINO-MODERN difference, however I suspect the simulations are performed using prescribed vegetation/land surface properties, which would actually have changed over the past few millions years. One way to tackle this question, would be to use alter the land surface in the simulation or to find a way to switch off the soil-moisture feedback in the RegCM3 simulation (perhaps by using inputting the modern soil moisture values somehow).

This is a good point and certain groups have tried to simulate the secondary land surface feedbacks in paleoclimate and modern simulations. Bonham et. al., 2009, ran Pliocene simulations with altered vegetation and found that this feedback is important in matching the

Pliocene proxy record. When they compared their vegetative induced precipitation anomalies with Haywood et. al., 2007 who prescribed an El Niño in the Pacific they found that the spatial patterns between the induced precipitation anomalies are the same, but the precipitation anomalies are enhanced in the simulation with a persistent El Niño. This leads the authors to believe that altering the vegetation will further enhance the precipitation anomalies that occur due to a permanent El Niño.

Revised text in results section 3.4.3

Previous research has shown that wet springtime months can lead to an enhanced summertime precipitation (Eltahir, 1998; Findell and Eltahir, 1997, 2003; Pal and Eltahir, 2002), and regional climate modeling experiments have been run which explore these types of feedbacks. Fischer et al., 2007, explored the feedbacks of soil moisture on the large European drought of 2003 and found that by decreasing the soil moisture quantities that this increased the strength of the European drought and induced secondary atmospheric circulation feedbacks. Seneviratne et al., 2006 used a regional model where they turned off the land-atmosphere interactions and found that this feedback is extremely important in understanding climate change in a world with increased atmospheric carbon dioxide. These studies illustrate that the land surface feedbacks resolved in regional models are important in controlling precipitation and atmospheric circulation. Also as described above in the seasonality of precipitation, the longer memory introduced into the regional climate system by the winter precipitation anomalies causes spring and summer to be moister. These results motivate why we show the seasonality of precipitation and its relationship with soil soil moisture feedbacks.

P213, l26--page 15. "preceding the summertime" is unnecessary.
This has been corrected in the text

Does white in the figure indicate a lack of statistical significance? If so, state this. Also there are only 7 colors used in a colorbar with 14 boxes.

Yes, the colorbar was adjusted to manually remove the insignificant data. We chose to only highlight the regions where the results are significant which is why there are only a few colors on color bar. This has been clarified in the figure caption.

I didn't feel that I needed to see the precipitation lag correlations as well as the relative humidity; simply stating that the correlations were weaker would be sufficient.

Good point, this will be taken out and adjusted in the text. The revised text will still mention that lag correlations between precipitation and soil moisture are less than the relative humidity and soil moisture correlations.

Revised text in section 3.4.3

The correlation analysis was also calculated between relative humidity and soil moisture for the NINO simulation. The geographic areas of statistically significant results remain the

same as the results presented above, but the magnitude is increased in the relative humidity and soil moisture correlations.

<u>**Discussion**</u>

I didn't fully understand the arguments in the first paragraph of p217-page17. Are you trying to retrospectively justify using the RegCM3? Perhaps a single additional panel of the NINO-MODERN JJA anomaly in the low-resolution model in Figure5 will make this point more effectively.

We have made a number of changes in order to clarify the motivation of using RegCM3. As detailed above and in the response to Reviewer #2, these include (1) adding text to the Methods section clarifying that our primary motivation for high-resolution nesting is to better resolve fine-scale processes that can be important for the response of regional climate to changes in global-scale forcing or changes in large-scale climate dynamics; (2) adding text to the Methods section clarifying that RegCM3 is better able resolve the regional precipitation features in the U.S. than CAM3.0; (3) adding the new Figure 1 showing the simulated NINO-MODERN precipitation and the proxy-inferred moisture differences-from-present, along with text clarifying that the differences in the simulation of baseline precipitation between the low- and high-resolution models are particularly evident over areas for which proxy records of Pliocene and Miocene precipitation exist, including the topographically complex Western US in winter and coastal areas of the eastern U.S. in summer; and (4) adding text to the Results section stating that the regional model simulates more wide-spread moistening in the Western and Central US than the global model, and the proxy-inferred drier conditions over the Pacific Northwest are resolved in the regional model, but not in the global model

The figure comparing the CAM3.0 and RegCM3 baseline seasonal precipitation is now Figure 3. We will highlight Figure 2 in the beginning of the paragraph in the discussion so readers understand how RegCM3 is different from CAM3.0 results. This figure was included as additional motivation for why RegCM3 is important for our study. RegCM3 is able to resolve precipitation over topographical regions and has been proven to resolve small dynamical features which are important for monsoonal circulation (described in methods 2.1).

In addition, we will devote a new section to describing the comparisons between CAM3 and RegCM3 (new-Section 2.2).

I was surprised that the point discussed in the second paragraph of p217 had not been mentioned previously. Typically El Nino's are strongest in DJF, with much more moderate SST anomalies in the summer. I would therefore expect the strongest differences between your permanent El Nino forcing to occur in the summer. (I think the differences between impact of permanent El Nino in Barreiro et al. 2006 and the patterns shown in Huybers Molnar, 2007 arise from this difference in methodology).

The authors agree that this is an interesting point and will be mentioned earlier in the text. Since this sensitivity experiment assumes that there was a change in the mean state of the EEP resulting in SST anomalies all year. Boreal summer teleconnections induced by a permanent El Niño is less understood dynamically which is why we look at the entire seasonality in our results. Futhermore, the response during the summertime is partially dependent on the El Niño SST pattern (as you state), but even though there is a strong El Niño present in the summertime does not necessarily mean that teleconnections will be stronger than during a normal El Niño event. In our permanent El Niño simulations this ends up being the case.

The discussion is not the place to introduce the possibility of increased El Nino frequency, especially without any further mention or citations (p218, l24). I am not sure that you need to discuss this possibility at all.

The part about El Niño frequency is removed from this sentence.

Has the existence of a permanent El Nino actually been proposed for the Miocene? I am not certain that it has (if it has been, just include a citation).
Yes, see Lyle et. al., 2008 and Fedorov and Philander, 2003.

To better illustrate our motivation we quote Philander and Fedorov, 2003.

"Specifically, we propose that a cooling of the deep ocean, documented by Lear et al. [2000] was accompanied by gradual shoaling of the thermocline. In the early Cenozoic, when temperatures in the deep ocean were in the neighborhood of 12C, the thermocline was so deep that the winds were unable to bring deep, cold water to the surface in the upwelling zones of low latitudes. El Niño conditions were permanent. That continued to be the case, even as the thermocline shoaled gradually, until about 3 Ma."

Conclusions

P219, l21 please use "atmosphere models", as "climate models" implies coupled atmosphere-ocean models to me.
This is reworded in the text.

Revised text in conclusions page 24:

By using a high resolution global general circulation model and nested regional model here we explored the possible atmospheric dynamics that could develop if the ocean was in a permanent El Niño-like mean state.

P219, l22. Please could you reword your clause about ENSO deviation? You have solely explored changes in the mean climate state and not discussed changes in climate variability. Although I do expect the two to be related, we do not yet know the nature of the relationship. I feel it important to recognize this distinction, especially in the conclusion.
This is a good point and this sentence is reworded in revised manuscript.

Revised text in the conclusion page 24:

By using a high resolution global general circulation model and nested regional model here we explored the possible atmospheric dynamics that could develop if the ocean was in a permanent El Niño-like mean state.

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